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**Empirical Techniques for the Study of Acceleration  
Mechanisms in the Space Environment**

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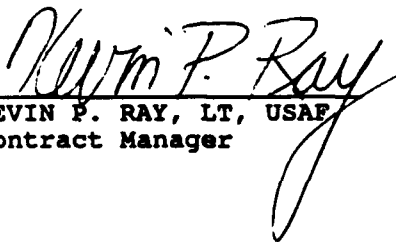


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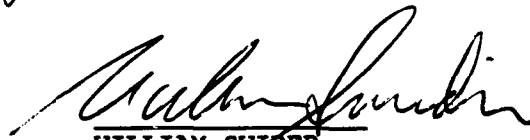
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## Contents

Forward.....	iv
1. Wave-Particle Interactions.....	1
2. Diagnostics.....	3
High Frequency Buncher Mode .....	5
Low Frequency Auto-Correlation Function .....	6
Beam Cross Correlation .....	6
Neural Network Algorithm .....	6
3. Conclusions .....	7
References.....	8



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## **Forward**

This contract work focused on the development of useful empirical models for the study of particle acceleration mechanisms in the space environment. The goal was to further the design of a new generation of state-of-the-art diagnostics to measure these effects and provide information for the development and verification of accurate theoretical models.

These models were to be generated from examination of the existing data base from the Defense Meteorological Satellite Program (DMSP), analysis of data from the Combined Release and Radiation Effects Satellite (CRRES), and the extrapolation of these measurements into other regions of the space plasma environment.

This report discusses wave particle interactions and their relevance to particle acceleration (and deceleration) in the space plasma environment. Particular attention is paid to the physical manifestations of these interactions. Several diagnostic strategies are proposed. Interpretation of DMSP data has provided some means of estimating the magnitude of natural wave-particle occurrences and the dynamic range necessary for a versatile diagnostic. Details of a particle correlator that is being flown on CRRES have been reviewed. The CRRES experiment has not been on orbit long enough to evaluate the particle correlator performance in a natural environment. Preliminary data, however, indicate that the experiment is operating properly.

The model predictions developed in this research have been used to help design an advanced particle correlator that will be flown on the Tethered Satellite System 1 mission aboard the Space Shuttle's STS-46 flight.

## 1. Wave-Particle Interactions

Wave-particle interaction is important as one of the few processes through which energy can be exchanged between the different particle populations in the collisionless plasma found in the natural space environment.

When charged particles are in velocity resonance with waves, either particle energy is transferred to the waves resulting in wave amplitude growth and particle deceleration, or wave energy is transferred to the particle resulting in particle acceleration and wave damping. In either case, charged particles in velocity resonance will become phase bunched with the wave. This is observable as fluxes of particles at the resonant velocity (energy level) modulated in time at the wave frequency. Measurements of these particle modulations as a function of frequency, energy level, and particle direction of motion, allow the identification of those regions of particle velocity space contributing to wave growth and wave damping.

There are several natural and artificial sources of these waves in which we are interested. Cyclotron motion is the basic movement of a charged particle relative to a magnetic field. One type of wave results from ion and electron gyromotion and its frequency is given below,

$$\omega_{ce} = \frac{e\bar{B}}{m_e} \quad \omega_{ci} = \frac{e\bar{B}}{m_{ion}} \quad (1)$$

The gyrofrequency,  $\omega_c$ , varies directly with the magnetic field strength ( $\bar{B}$ ) and inversely with the mass of the particle ( $m$ ). Thus one would expect higher frequencies in regions of space where magnetic fields were greatest, i.e. near planetary bodies with large magnetic fields.

A plasma, under certain conditions, can be modeled as a system of coupled oscillators. This oscillation is the result of the existence of long-range forces between plasma particles. Plasma oscillations produce waves that travel at the plasma frequency. The plasma frequency varies as the square root of the number density ( $n_0$ ) of the plasma,

$$\omega_p = \sqrt{\frac{n_0 e^2}{E_0 m}} \quad (2)$$

The plasma frequency can be viewed as the natural vibrational frequency of the medium. The plasma frequency can provide a measure of electron density in a plasma.

Waves travel along an axis perpendicular to the magnetic axis in plasmas that are magnetically confined. A wave that has its  $\bar{E} \perp \bar{B}_0$  is an extraordinary. One type of extraordinary wave resonance is at  $\omega_h$ , the upper hybrid frequency. Including ion motion yields the lower hybrid.

$$\omega_h = \sqrt{\omega_p^2 + \omega_c^2} \quad \text{and} \quad \omega_l \approx \sqrt{\omega_{ce}\omega_{ci}} \quad \text{where } \omega_p/\omega_c \gg 1 \quad (3)$$

Values for these frequencies may be estimated using known information about the space environment<sup>2</sup>. Specifically, at the STS altitudes,  $n_0 \approx 10^5 \text{ cm}^{-3}$  and  $\bar{B} \approx 5 \times 10^{-5}$  Teslas. Local conditions can result in these values varying by as much as a factor of 100. Never-the-less these values result in the following frequency ranges:

$$\begin{array}{lll} \omega_p = 0.5 - 5 \text{ MHz} & \omega_{ci} = 35 \text{ kHz} & \omega_{ce} = 1.5 \text{ MHz} \\ \omega_l = 33 \text{ kHz} & \omega_h = \omega_p & \end{array} \quad (4)$$

where  $1\text{Hz} = 2\pi \text{ radians/sec}$ . These approximations provide the frequency regimes that an instrument should focus upon.

## 2. Diagnostics

Having established some frequency ranges of interest, we have looked at various diagnostic techniques that may provide accurate measurements of wave particle-interactions in the space environment. Preliminarily we looked at the SSJ/4 instrument on the DMSP<sup>3</sup>. The output of the SSJ/4 consists of digital counts accumulated over discrete periods of time (98 msec). This sort of digital counting mode is typical of many charged particle detectors used in space. Frequency signatures of a shorter period are integrated over the accumulation period. However, the count rates do yield data on an energetic particle population that exceeds the thermal range of a cold plasma for the DMSP's satellite altitude. These non-thermal plasma components consist of auroral precipitated particles, some of which have undergone wave particle interactions that modify their energy spectra. The DMSP also has a Langmuir probe measuring these cold plasma characteristics. Comparing these two data sets, one can detect some wave-particle interactions.

The most obvious interaction is manifested in the detection of the spacecraft charging to potentials well above the local plasma temperature. This charging is seen by the appearance of a sharp ion peak at the charge potential. The charge on the spacecraft accelerates the cold plasma ions (whose energies are well below the lower energy threshold of the SSJ/4) toward the spacecraft. The resultant ion flux appears to the SSJ/4 as a monoenergetic ion beam whose energy is the charge potential. For such an event to occur, the ambient plasma density has to be too low to provide neutralization and there must be a high energy precipitating electron flux. A few of these events have been observed, but a recent review of the DMSP SSJ/4 data could not isolate any events with enough certainty to allow using them to model spacecraft charging to test a charge detection algorithm.

The next experiment set that we reviewed was the Spacecraft Particle Correlator Experiment (SPACE) that is part of the Low Energy Plasma Analyzer (LEPA) flown aboard the CRRES<sup>4</sup>. This device measures the temporal modulations of electron and ion fluxes as a function of particle energy. The SPACE experiment uses the raw count rate data from the ion and electron sensors. These data consist of 16 coarse and 8 fine angular zones for each species taken over 128 logarithmic energy steps. An input from the CRRES magnetometer is used to select probable channels for correlation, thus reducing the amount of raw data to be processed. Two correlation strategies are followed.

When SPACE has a high data rate and the energy range is stepped every half spin period (15 sec), an electron zone is selected that maps all pitch angles in a  $\frac{1}{2}$  spin period due to  $\bar{B}$  field symmetry. This selection is accomplished by using the magnetometer data. A series of auto-correlation functions (ACF) is generated such that:

$$R(\tau) = \sum_{i=1}^{i=64} C_i C_{i+\tau} \quad \text{from count samples } C_i \dots i=1 \text{ to } 128 \quad (5)$$

which results in a 64 point ACF. These ACF's are summed over  $\sim 5^\circ$  pitch angle. The summed  $R(\tau)$  is then downlinked. At the same time, the 16 ion channels are summed

in groups of 4 adjacent 8° zones. This results in a low frequency ACF of the form  $R(\tau, E, \alpha)$ , where  $\tau$  is the lag,  $E$  the energy, and  $\alpha$  is the angular range (-36°).

A different method is used when the SPACE is in a low data rate configuration. A CRRES wave experiment provides an output to the SPACE resulting from electric field measurements. The wave experiment detects local low frequency electric field variations via an antenna and a sensitive amplifier. The detected frequency ( $1 \text{ Hz} < f < 30 \text{ kHz}$ ) is saturation-amplified inside the SPACE to produce a digital frequency that is twice the rate of the analog wave receiver output. The digital frequency is used to time accumulation intervals that are twice the frequency detected by the wave experiment. These accumulations are compared in alternate cycles to derive the modulation significance with respect to the detected frequency.

$$\text{modulation significance} = \frac{|C_0 - C_1|}{\sqrt{\frac{C_0 + C_1}{2}}} \quad (6)$$

where  $C_0$  is the even accumulation and  $C_1$  is the odd accumulation.

After examining the DMSP SSJ/4 data base and reviewing the CRRES LEPA SPACE experiment, we wished to model experimental techniques appropriate for the Tethered Satellite System 1 (TSS-1) mission. The particle correlator methods of SPACE on LEPA would need to be modified to accommodate the TSS-1 mission. The TSS-1 activities should certainly perturb the plasma and it is reasonable to anticipate significant wave particle interactions during the mission.

The experiment that we have modeled is the Shuttle Potential and Return Electron Experiment (SPREE). The experiment consists of two electrostatic analyzers (ESAs) mounted on rotary tables that sweep the ESAs' viewing direction through 180° of azimuth. The ESAs are mounted in the shuttle bay and are oriented so that their 100° field of view extends from the local horizon through 10° past their zenith. The sensitivities of the ESAs differ by a factor of 100 to increase their overall dynamic range. Each ESA has 10 electron and 10 ion channels.

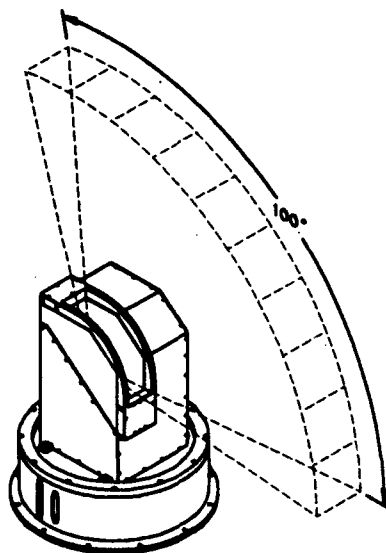


Figure 1: SPREE ESA Mounted on Rotary Table

Three separate methods have been devised to discriminate frequency modulations of the observed particle fluxes: a high frequency buncher mode, a low frequency auto-correlation mode, and a beam cross correlation mode.

#### High Frequency Buncher Mode

Electrons are expected to undergo interactions with waves at frequencies in the range of 1-10 Mhz. The local electron gyro frequency,  $\approx 1.4$  MHz, the local upper hybrid frequency, 1-7 MHz, and lower harmonics of these frequencies are the wave sources. These high frequency modulations are superimposed on counting rates that are anticipated to be of the order of 100,000 counts per second or less. A one bit "buncher" mode of correlation can be used to de-convolve high frequency data from these counting statistics. The time of arrival between successive electrons can be measured by a 20 MHz clock. A histogram of the number of measured separations as a function of separation units (50 ns) can be accumulated over a period of time. This is the equivalent of averaging many one bit correlation functions, each with only two bits set. This technique has been used successfully to identify modulations at Megahertz frequencies present on the natural auroral beams above auroral arcs.<sup>5</sup>

To accommodate the expected wide range of counting rates and still perform some meaningful correlations in reasonable time and space, the high frequency range should be sub-divided into three frequency regimes, 0-.625 MHz, 0-2.5 MHz, and 0-10 MHz. This can be accomplished by selection of various multiples of the clock units to create a histogram.

Six electron channels are correlated at a time. All of the 20 electron channels and all three of the frequency bandwidths can be commutated through the correlation process every nine minutes.

### **Low Frequency Auto-Correlation Function**

Low frequency auto-correlations can be performed in the frequency band from 0 to 10 KHz. This frequency range contains the lower hybrid frequency and the ion gyro frequencies ( $< 1$  KHz). Naturally occurring modulations at these frequencies are expected both in ions and electrons.

Twelve independent simultaneous auto-correlations may be performed by twelve 80C31 micro controller units (MCU). A commutation system would allow these MCUs to process all forty data channels (20 ion and 20 electron) using three different bandwidths: 0-10 kHz, 0-5 kHz, and 0-1.3 kHz. The modulation detection efficiency for such a system would range from 72% with the 10 kHz bandwidth to 99% for the 5 and 1.3 kHz bands. The 80C31 MCUs can be controlled by a dedicated 80C86 which will supervise all of the SPACE operations and communicate with the rest of the SPREE via a "mail box" scheme in shared memory.

### **Beam Cross Correlation**

Part of the TSS-1 mission consists of electron guns used to inject the tether current collected from the satellite back into the local ionosphere at the Shuttle end. These electron beams can be actively modulated at kilohertz frequencies which will in effect "tag" the beam electrons with this artificial frequency. Depending on frequency and plasma conditions, the modulated beam may trigger natural emissions. Any portion of the electron beam returned to the shuttle can be identified from its known frequency signature. Furthermore, any beam electrons that have undergone acceleration or deceleration, or natural electrons which have interacted with the beam modulation can be identified by the correlator.

Both electron gun systems that will operate during the TSS-1 mission can provide synchronization signals to the SPACE instrument so that it will know when a gun is emitting. For each channel analyzed, counts are binned into two counters depending on whether the electron guns are on or off. A separate count of a stable oscillator provides a measure of the total time spent on or off. If there is no significant modulation present in the accumulated counts, then the variation of these two sums should be of the order of that expected of Poisson statistics taking into account the different total times spent in the two states. This will give a direct measure of the significance of any modulation present in the particles at the beam modulation frequency.

### **Neural Network Algorithm**

The correlation functions operating on the SPREE ESA data will produce a prodigious amount of data. The real-time telemetry stream is limited and therefore most of the SPACE data will have to be recorded by on-board tape recorders for post-flight analysis. The real-time data stream could include some indication of the significance of the SPACE correlations so that the over-all TSS-1 mission can be optimized to achieve the maximum scientific data return.

A neural network approach may be used to develop a rapid and succinct status report of the SPACE operation to include in the real-time data stream. This report

would need to contain some indication of the nature of the data being recorded by the on-board recorders and a functional verification of the SPACE operations. An "intelligent data analyst" can be designed to use a neural network to form a pattern recognition system. The network data will be pre-learned by a ground based personal computer using a few hours of processing. This will result in an algorithm that SPACE could apply to a data set in a matter of milliseconds. The algorithm would consist of a look-up table stored in ROM and be used during flight operations to provide data quality assessment in real time.

### **3. Conclusions**

The techniques of particle correlation can yield useful data from particle detection instruments whose outputs consist of digital pulses. A wide frequency range may be covered with excellent detection efficiency. The additional information may be used to model wave particle interactions. This technique allows the coupling of local measurements to remote regions, providing an exceptional analysis tool.

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